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From risk to WEF security in the city: The influence of interdependent infrastructural systems

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ABSTRACT

Across the planet, interacting threats are converging in urban areas beset with pressures brought on by global processes such as urbanization and climate change, and the challenges of creating water, energy and food (WEF) security for their populations. With an increased probability of floods and other extremes, goes a heightened potential for cascading effects as WEF security is at risk from an array of tightly bound interdependencies undergirding the WEF nexus. Such interdependencies heighten risk for generalized disruptions, as, for instance, when heavy precipitation triggers a breakdown of transportation infrastructure, leading to failures in energy generation, and provision of food and water. In this paper, we apply a framework to examine how interdependent WEF infrastructural systems mediate the risks that climate extremes pose to urban WEF security. Given that urban WEF security often hinges on dynamics that take place in regions outside city boundaries, we also examine the effect of this dependence on urban FEW security risk. We compare the pre- and post-event governance and infrastructural conditions shaping WEF security in four cities: Boulder Colorado and New York (USA) illustrative of WEF security risks posed by low probability high impact extreme events; and Accra (Ghana) and Mexico City (Mexico), illustrative of governance and infrastructural arrangements that can fail even under low risk high probability extreme events. We find that complex technological and governance failures can amplify negative impacts from extremes. Conversely, institutional actions and infrastructural supports can mitigate these impacts. By understanding interdependencies, cities can anticipate and avoid cascading effects on WEF systems. We reflect on how commonalities and differences in sociodemographic, economic, technological, environmental, and governance configurations relate to different capacities to mitigate risks and adapt.

1. Introduction

Urbanization and climate change are coalescing to generate increased risk of floods, droughts and other extreme hazards. As they interact with human systems, these hazards create a heightened potential for cascading effects threatening people's security by undermining the sustainable and equitable utilization of water, energy and food (WEF). We posit that cascading effects depend on specific urban sociodemographic, economic, technological, environmental, and governance configurations. Hence, their diffusion over time and across space is mediated by interdependent vulnerabilities in governance, critical infrastructure and other domains of the city. While the effects culminate in the urban realm, causes and drivers for change also lie in the regions the city depends on (Pescaroli and Alexander, 2015). At the same time, these events can offer options to mitigate risks, adapt, and foster security.

The provision of WEF resources, a key component of basic supply systems, presents a major challenge for sustainable urbanization. Global projections indicate that by 2030, the world's population will "consume about 30 per cent more water, 40 per cent more energy, and 50 per cent more food than today"(Leese and Meisch, 2015), resulting in increasing resource competition among urban, industrial, and agricultural uses. While WEF infrastructure-systems in many developed countries are in many cases deteriorating, cities in rapidly developing countries have failed to develop infrastructure that keeps pace with the dynamics of urbanization (Kraas et al., 2016). A clear under-investment exists characterized by backlogs and under-maintained infrastructure. Estimates indicate that globally, around US$57 trillion is needed for infrastructure investment between 2013 and 2030 in order to support sustainable development (McKinsey Global Institute, 2013).

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[1] http://www.ral.ucar.edu/csap/themes/urbanfutures.php.

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In recent years, the links between water, energy and food, also known as WEF nexus, have received increased interest in policy, business and academic circles (Hoff, 2011). According to nexus thinking, the world's WEF systems are significantly stressed and suffering shortages due to their interactions with planetary anthropogenic processes, such as urbanization, globalization and climate change (Bizikova et al., 2013). WEF nexus is therefore a major global risk, requiring explicit analysis of threats and the socio-environmental factors explaining differences in vulnerability. Proponents of nexus thinking also point that WEF systems are so interdependent that actions in one often affect the others, and suggest integrative approaches such as resilience thinking, socio-ecological systems analysis, and integrated resource management to analysis, planning and action in order to reduce tradeoffs and enhance synergies (Hoff, 2011).

While the literature acknowledges the influence of climate change on WEF security (Villamayor-Tomas et al., 2015), in this paper we address two questions that have received less attention. How do interdependent WEF infrastructural systems mediate the risks that climate extremes pose to urban WEF security? Given that urban WEF security often hinges on dynamics that take place in regions outside their boundaries, what is the effect of this dependence on urban WEF security risk? We find this perspective and our approach to urban WEF security important for many reasons. Global climate change will most probably lead to more frequent and intense extreme events (Henstra, 2012). Urban areas concentrate economic and socio-political activities. If cities are facing security risks, the risk will cascade also in spatial terms to peri-urban areas and to the regions providing WEF resources to cities (Panteli et al., 2016). The ideal of the modern city closely relates with interdependent, networked infrastructures that can make the city more vulnerable or more resilient, a feature that drives our research interest.

In this paper, we lay out a framework to address these questions through an examination of the infrastructural and governance conditions shaping WEF security risks in four cities: Accra, (Ghana), Boulder, Colorado (USA), Mexico City (Mexico), and New York (USA). These cities are illustrative of other urban areas from the Global South and North facing climate threats to WEF security, but differing in governance, infrastructure and socio-economic conditions. While in New York and Boulder, governance regimes fail only under low probability high impact risks, such as those unleashed by Hurricane Sandy and the September 2013 Boulder flood, for instance, Accra and Mexico City are vulnerable to high probability low impact risks, and face huge challenges securing WEF infrastructures and services in sustainable and fair ways. Our exploration will serve as a basis to examine how common WEF nexus patterns and context specific conditions relate to differentiated capacities and options for sustainable responses to urban WEF security challenges.

To accomplish our goal, we briefly discuss concepts that are fundamental to our conceptual framework, such as urban WEF security risk and domains of WEF risk, multilevel interdependencies, and cascading effects (Section 2). We then briefly describe the study cities and the methodological approaches to WEF security, which can be used at the city-region level (Section 3). The examination, in Section 4, of WEF conditions in the four cities will help us draw some conclusions and suggestions for future research (Section 5).

2. Conceptualizing WEF security risks and multilevel interdependencies

2.1. WEF security and climate risk

The WEF nexus debate is increasingly linked to the notion of security that recently emerged in sustainability science with the concepts of water security (Cook and Bakker, 2012), energy security (Yergin, 2011), and food security (Godfray et al., 2010). We will suggest in this section a risk approach to 'security' that points to the conditions of possibility or potential for harm, rather than to existing threats which inevitably prompt emergency measures, friend versus enemy thinking, or militarization against defined threats, or direct causes of harm (Corry, 2012; Floyd, 2008).

WEF security emerged as a concept and a series of policies around environmental and climate security (Floyd, 2008). While the notion of security mostly revolves around a threat to a referent object, and a series of policies and actions to protect it, fundamental disagreements in framing, conceptualization, methods and scope persist, with three debates of relevance to this paper. The first of these debates centers around whether security is an ontological issue that researchers can objectively analyze using quantitative methods and models (positivistic approach), or a contested issue, where researchers analyze similarities and differences in 'what actors make of it', and arrive at relative approximations using qualitative methods such as cognitive maps (constructivist approach, Copenhagen school). In such approaches, for instance, mapping security requires that we ask who is to be secured, what is to be secured against, and what actions and policies may create that security (Floyd, 2008; Romero-Lankao et al., 2017; Trombetta, 2008).

Second, scholars and practitioners either embrace a broad and holistic (human security) or narrow (national) conceptualization of security (Owen, 2004). In the national security approach, planetary trends such as climate change, migration, and the scarcity of WEF resources pose dangers to the availability of natural resources, thus, the viability of the nation-State, and demand policy interventions by public and private decision-makers seeking to secure these resources. Proponents of the former interpretation frame WEF security as the protection of the *vital core* of human life and livelihood, based upon the freedom and capacity populations have to pursue their lives with dignity (Adger et al., 2014; Owen, 2004). The vital core entails two kinds of needs and rights: universal and material. The material rights include such elements as sustainable access to water, energy, and food, which are fundamental for survival, and sustainable livelihoods; while the non-material rights include cultural elements, such as identity, sense of place, social recognition, and inclusion. All of these can affect a population's WEF security, and in particular, its capacity to respond to climatic events, such as floods and droughts that have the potential to result in harm (Adger et al., 2014; Owen, 2004).

Third, there are two main approaches to WEF nexus issues, which differ in their emphasis on security or on risk (Corry, 2012). In the first case, the focus is on an existing threat, while in the second, it is on the social and environmental domain dynamics determining the potential for harmful events. While security thinking leads us to look for the 'direct causes' of harm to urban populations and places, risk analysis leads us to examine the factors or 'constitutive causes' of possible harm. This paper will focus on risk. We seek to understand the role of interdependent infrastructural systems in shaping the conditions of possibility for uncertain and harmful outcomes posed by extreme climate change events (Corry, 2012). Our approach to urban WEF security, thereby, differs from framings focused on securitization (Leese and Meisch, 2015), in which an actual threat is claimed that requires action plans to defend a valued object under the politics of emergency. We want to identify WEF risk domain factors in order to suggest actions seeking to reduce vulnerability and foster urban actors' capacity to mitigate risk and adapt.

2.2. Domains of WEF security risk

Risk can be conceptualized in many ways (Renn, 2008), for example, as the probability of occurrence of an extreme hazard such as flood multiplied by its multiscale consequences if it occurs (Field et al., 2014). We define WEF security risk as the possibility for uncertain and harmful outcomes, where something of value is at stake (Field et al., 2014). Risk results from hazard or threat, exposure and vulnerability of populations, WEF assets and economic activities (Fig. 1). Hazards can

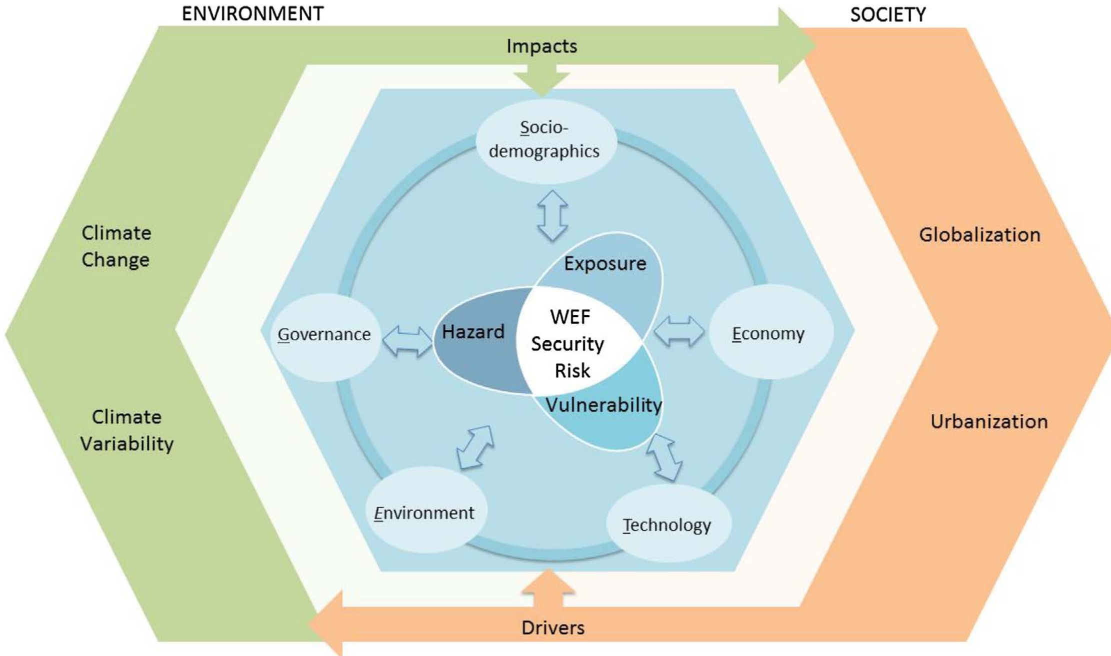

Fig. 1. WEF Security Risk. This conceptual diagram shows WEF security risks resulting from hazard, exposure and vulnerability, and interacting with five interacting urban development domains: Socio-demographics, Economy, Technology, Environment, and Governance. These domains operate within a wider context of interactions between environment and society. Source: own based on (Romero-Lankao and Gnatz, 2016).

be extremes, such as storms and floods, or slow-onset events such as the urban heat island or sea level rise. Vulnerability, or the propensity to be adversely affected, is a function of exposure, sensitivity, and capacity (Adger, 2006; Romero-Lankao and Qin, 2011). Exposure is the presence of populations, WEF infrastructure, or assets in places that can experience hazard. While people and places can be susceptible to hazards, they also have capacity or the potential to modify their features and behavior to mitigate or adapt. Capacity is the unequally distributed pool of resources, assets, and options governmental, private, and nongovernmental urban actors can draw on to mitigate and adapt to WEF security risks, while pursuing the goals they value (Romero-Lankao et al., 2016) (Fig. 1).

Major disagreements remain about the drivers of risks induced by urbanization and climate change. Some of these disagreements relate to fundamental differences in the definition of urban, based on population size, built-environment form, and economic function. Some scholars see cities as socio-ecological systems (SES), whose multiscalar dynamics and management by governmental and nongovernmental actors have two related implications for WEF security risk (McPhearson et al., 2016). First, cities exert environmental pressure through their use of energy, water, land, food and other resources, not only on their own local environment but also on the regional and distant areas providing these resources. Secondly, therefore, through their extraction, storage, distribution, and use of resources, cities shape the risks to WEF security of their residents and of populations in areas beyond their boundaries. For instance, Mexico City's ability to secure water from an external basin in Cutzamala is affecting the agricultural livelihoods of indigenous Mazahua communities in Cutzamala, even as it is emitting greenhouse gases through its energy-intensive system that pumps water up over for more than 1000 m (Romero-Lankao, 2010). To add even more pressure to this system, climate change is now putting Mexico City at risk from projected reductions in water availability (of between 10 and 17%)(Martinez et al., 2015).

While we agree with the many scholars that see cities as SES systems, we find this concept too abstract to produce an operational understanding of system interactions on the ground. Therefore, we conceptualize *urban areas* as socio-ecological systems (Folke et al., 2005; Ostrom et al., 2007), representing five (SET*E*G) interacting domains determining the potential for droughts, floods and other hazards to result in harm: Socio-demographics, Economy, Technology, Environment, and Governance (Arup, RPA, n.d.; Romero-Lankao and Gnatz, 2016) (Fig. 1).

Features of socio-demographics, such as the young or old age population balance of a city, or the behavioral practices of a demographic group shape risk. Examples include populations living along coasts forests and other risk prone areas based on lifestyles (aesthetic desirability of location) or lack of options. The vitality of an urban economy shapes productivity and inequality in access to assets and options to mitigate risk and adapt. If the urban economy favors capital owners and renters over the working populations, as it has in recent years in many cities worldwide, then the rate of return on capital increases faster than the rate of economic growth (Cohen and Simet, 2017). As wealth grows faster than economic output, economic growth accumulates in the hands of a few, and inequality or the wealth gap between the few and the rest of society increases (Cohen and Simet, 2017). This negatively affects the effectiveness of safety-nets determining capacity to respond to WEF security risks (Browning et al., 2006). It also determines spatial and temporal differences in access to WEF resources and options urban populations can draw on to respond to risks (Jepson, 2014; Romero-Lankao et al., 2016).

Technology, the third domain, is the means by which water, electricity, and food are transformed or conveyed for urban use, shaping WEF security risk as infrastructures determine availability and utilization of WEF resources; convey WEF wastes; and transform landscapes dynamics and water, carbon, and nitrogen cycles. WEF infrastructures such as power plants, roads, communication, electric grids, and *trans*-basin water supply systems, are a primary source of interdependencies because they can mitigate or amplify populations' vulnerability to climatic and non-climatic threats. From a socio-technical perspective, infrastructures – and, in particular, interdependent of networked infrastructures – constitute the material, cultural and political substrate of urban life (Coward, 2009). Therefore, the density of urban infrastructural systems has the potential to both link energy and water with food, and the cultural with the political symbolism, all of which makes infrastructural systems so constitutive of the urbanization of security.

*E*nvironment refers to the biophysical, climatic, ecological and

hydrological factors affecting an urban area's endowment of WEF resources and predisposition to hazards. Society and the environment are so intermingled in cities that the unequal distribution of technological and environmental factors affects a population ability to mitigate risk and protect themselves from hazards. For example, ecological and built environment services can mitigate or exacerbate vulnerability to heat extremes. This depends on whether an individual inhabits an older house of poor heat-protective design, and has to spend more on electricity to cool the living space; or whether the person lives in an area with tree shading, parks, and other ecological and built environment services. And this is shaped by policy decisions and political contexts.

Governance is the set of formal and informal rules, rule-making systems, and actor-networks from local to global level and across WEF sectors, both in and outside of government, shaping urban WEF security and the actions to mitigate and adapt to risks (Romero-Lankao et al., 2015). Governance structures the formal and informal incentives and sanctions that actors face when they make WEF security choices. Governance shapes WEF security risk inequalities through the legacies of political actions around land use and water planning; through investments and location of WEF infrastructure and service networks; and through some of the mechanisms of social exclusion (e.g., by class, gender and race). Particularly in cities, such as Accra and Mexico City, growth of both low-income informal housing and economies, and higher-income, gated activities and communities often occur in areas that provide environmental services, such as flood protection, water infiltration, and food, or are prone to landslides and floods(Romero-Lankao et al., 2016). Still, while some forms of growth in risk-prone areas enjoy state sanction, with secure WEF services provided by governmental authorities, others are stigmatized and criminalized (Roy, 2009).

For the purpose of this paper, we will define WEF infrastructural systems as interdependent networks of technologies, institutions, and actors shaping distribution capabilities that provide a reliable flow of WEF products and services essential to fulfilling many purposes. In particular, we focus here on the purpose of creating city wide capacity to mitigate risks and adapt (Rinaldi et al., 2001). While the focus will be on WEF infrastructures including electric power, natural gas and oil, water supply, and food and agriculture systems, we acknowledge the role of telecommunications, banking and finance, transportation, government services, health, and emergency services based on their interactions with the WEF nexus (Rinaldi et al., 2001). These systems interact and communicate with one other, i.e., they receive inputs and sends outputs, including resources, services, products and information. The input to an oil pipeline includes electricity to power the pumps, information and the actual demand for oil, while the outputs include the flow and provision of oil to external users and price signals. Learning results from utilities and operators capabilities to improve their performance and adjust their outputs, products and services to meet varying demands and respond to threats and disruptions.

2.3. Multilevel interdependences and cascading effects

The notions of interdependencies and cascading effects are useful to examine the mediating influence of WEF infrastructural systems in mitigating or amplifying the impacts from extreme events. The interactions between infrastructure elements can be either unidirectional, or dependent, such as when the state of one (e.g., transportation) influences the other (e.g., electric power); or multidirectional, or interdependent, such as when multiple infrastructures are connected as a system of systems (Rinaldi et al., 2001). Interdependencies are at the heart of the concept of cascading effects triggered by extreme events. Depending on characteristics such as location, experience, capability and linkages among elements, infrastructural systems can either mitigate or transmit shocks in cascading fashion within and beyond the city. The exact path of these cascading effects can be unpredictable and may have multiple effects in some or all SET*E*G domains- e.g., interruptions in energy provision and in communications, contamination of water systems, impairment of human health, which can result in disruption of city life.

The complex nature of the interdependencies can push WEF systems to cross thresholds (inflection points) where existing and relatively stable SET*E*G conditions (also called regimes) may give way to qualitatively different ones. Shifts can include a single transformation, confined to a particular domain, such as a local ecosystem becoming unusable for a certain time, for instance, after a flood or a landslide (Folke et al., 2004; Kinzig et al., 2006; Scheffer et al., 2009). The possibility also exists for regime shifts that trigger other domain shifts (e.g., relocation of populations, destruction of critical infrastructure and civil mobilization) in cascading fashion opening possibilities for transformations in some or all SET*E*G domains to take place, and resulting in a governance shift, and a new WEF security contract (Pelling and Dill, 2009). Two important questions are whether these cascading regime shifts lead to highly sustainable new regimes or less desirable ones, and who defines a desirable regime. This paper won't answer these questions, but only acknowledge that, while socioecological thresholds are contingent upon interactions among environmental and social processes, governance thresholds are integral to the way urban actor-networks work, with definitions of what is desirable and bearable contingent upon ethics, politics, power, and culture.

WEF security risk is multiscale. Infrastructural systems providing WEF resources to cities create effects in WEF utilities, distribution systems, and people's livelihoods far from the demarcations of city limits, and are affected by actions and processes that go beyond their boundaries. We will show in section 4, how dependency of Accra and Mexico City on external locations, such as Lake Volta (Ghana) and Cutzamala (Mexico) that provide them with WEF resources (Romero-Lankao et al., 2017), can be a source of vulnerability to extreme events posing risks to WEF security. Our risk approach is a means to connect human security with the drivers and domains shaping hazard, exposure, and vulnerability complexity. It is also useful to understand that governance factors such as under-investments, or mal-investments in infrastructure, or policies that favor investments in some areas of the cities in detriment of others create inequalities (Pelling and Dill, 2009), particularly as urban dynamics become increasingly dominated by interdependencies and cascading effects aggravated by climate change.

3. Study design

3.1. Operationalizing WEF security risks and interdependencies

Key to efforts seeking to link research to practice, is to map the framings or measure the factors and attributes of WEF security risks (Floyd, 2008; Kalliojärvi, 2017). However, challenges exist, independently of whether scholars use constructivist of positivist approaches. The former, with the purpose of using a theory of WEF security risk as an analytical model to map how actors frame a threat or hazard, and what actions they claim as needed to defend the vulnerable system against that threat (Wæver, 2011). The latter with the goal of using, aggregating or correlating data and indicators to test a theory of WEF security risk.

Scholarship measuring WEF-security risks, which has developed indicators of availability, access and utilization of water, energy, and food (Bizikova et al., 2013), has focused on the administrative boundary of nation states (Bogardi et al., 2012; Godfray et al., 2010; Grey and Sadoff, 2007; Sovacool and Brown, 2010), and to a lesser extent on urban areas and their regions. In capturing urban WEF security risks, which are multivariate and multifaceted, the choice of indicators depends on the theoretical approach used, which varies across WEF sectors and levels, and in terms of the domain variables that can be included, with differences often dependent on disciplinary perspective, definition and scope. Additional challenges result from data constraints.

Various methods are used to map the framings of WEF-security (Floyd, 2008; Kalliojärvi, 2017), or to measure WEF-security indicators, which are then integrated into indices (Romero-Lankao et al., 2016; Sullivan et al., 2006; Thapa et al., 2014). For instance, some scholars combine two indices to capture the quantity or availability of a resource as a proxy for security (Falkenmark et al., 1989, 2007). Other scholars apply tools to capture the multifaceted nature of security in one of the sectors. For example, a water, energy or food poverty index connects physical indicators of resource availability with socioeconomic indicators of unequal development (Khandker et al., 2010; Maitra and Rao, 2015; Nussbaumer et al., 2012; Sullivan, 2002; Sullivan et al., 2006). Nonetheless, these methods stop short of the daunting effort of incorporating the SET*E*G domain dynamics shaping urban security risks in the three WEF sectors, thus, representing the complexity of urban areas and their regions (Romero-Lankao and Gnatz, 2016). Nor do they help to determine how WEF interdependencies mediate the cascading effects triggered by an event.

Tools to map infrastructure interdependencies and cascading effects include matrices, wheels, fuzzy mental models, and tables graphically representing the direction of interdependencies as well as the direct or indirect path of events involved in cascading effects (City of Amsterdam, n.d.; Pescaroli and Alexander, 2015; Rinaldi et al., 2001). Secondary data, focus groups, workshops, and semi-structured interviews help to analyze different ways of framing interdependencies and cascading effects. In this paper, we will build on our prior work in selected cities, together with secondary data, to capture these interdependencies (see Section 4) in the cities of Accra, Boulder, Mexico City, and New York. To answer our two research questions, we will use Fuzzy Cognitive Maps to examine the mediating role of interdependent infrastructural systems on WEF security risks from climate extremes. We will also explore how these risks are influenced by the way cities both alter and depend on their regional and remote ecosystems.

3.2. The cities

With populations of 103 thousand, and of 2.9, 20.5, and 14 million people respectively, the city of Boulder and the metropolitan areas of Accra, Mexico City and New York face multiple WEF security risks that urbanization and climate change will likely aggravate. These range from sea level rise, coastal flooding and storm surges in Accra and New York to heat waves, droughts, heavy rains and associated flooding, and heat-island effects in the four cities. Here we will focus on Accra's 2015 drought, Boulder's September 2013 Flood, Mexico City's 2009 drought, and New York's 2012 Hurricane Sandy. Note that while for some scholars, drought conditions have persisted in Ghana since the Sahelian droughts of the 1970s and 1980s, others contend that, such as since 2015, drought recurrently hits Accra and Ghana (Rain et al., 2011).

The environmental domain shapes urban hazard dynamics (Fig. 1). For instance, decades of records from southwestern Ghana show a noteworthy reduction in rainfall and runoff linked to the influence of climate change (Rain et al., 2011). Topography and soil characteristics make Boulder and Mexico City particularly prone to floods and flash-floods. Location along the coast puts Accra and New York at risk from floods, storm surges and sea level rise. Still, many hazards result not only from long-term global and regional environmental change, but also from the social construction of risk through local changes in land, water, and energy use and from environmental processes induced by urbanization. For instance, in Accra and Mexico City, flooding is the consequence of blocked drains and urban expansion in flood-prone areas, but it is also the result of unequal patterns of urban development shaping inequality in hazard risk and access to land, energy, water and other resources and options. While some neighborhoods enjoy secure access to water, food, energy and land, poorer settlements and settlers, often living in risk-prone or peri-urban areas, usually don't have piped water, and are subject to energy and water rationing that could last several days (Romero-Lankao, 2010; Stoler, 2017).

The economic and governance domains, which are key determinants of infrastructural design and maintenance, also shape urban WEF risks (Fig. 1). In Accra and Mexico City, for instance, rather than by planning and the rule of law, both globalized and local markets have driven land uses and urban development, hence, WEF security risks, constraining local authorities' capacity to regulate resource use and land occupation. Housing construction is a fundamental policy instrument for job creation and economic growth, whereby, compliance with zoning and policies is undermined, the rule of law is subject to negotiations between involved parties (with the danger of corruption), and virtually no consideration is given to WEF security and environmental protection (Romero-Lankao et al., 2015). Even while land use regulations and policies in Boulder are fairly strict, and frequently drafted with hazard mitigation in mind, extreme hazards are posing governance challenges. For instance, changes in the course of rivers caused by the September 2013 flood rendered existing flood maps practically useless in the evaluation of land use permits (MacClune et al., 2014).

According to current models, global warming is likely to alter the existing environmental conditions influencing hydro-ecologic extremes (Revi et al., 2014; Satterthwaite et al., 2007). Studies suggest that there will be increases in mean temperatures in all four cities, decreases in mean precipitation in Boulder and Mexico, and increases in mean precipitation in New York. Expected changes in extremes that differ from known weather patterns include more intense droughts, a decrease in the number of areas experiencing freezing temperatures (0° C or less), increased variability of rainfall (e.g., in the Volta Basin, Ghana), more intense precipitation events, and more frequent heat waves (Niang et al., 2008). Sea level rise will likely affect low-lying areas in Accra and New York and interact with storms and surges to produce floods (Horton et al., 2008; Sagoe-Addy and Addo, 2013). Interestingly, however, global climate risks exacerbate local processes. For instance, in Accra coastal erosion is to a larger extent the result of illegal sand mining (sand that is needed for housing construction) rather than sea level rise as such (Bruns et al., 2013), but sea level rise exacerbates the risks to WEF security.

Driven by broader processes – e.g., urbanization – climate change and variability are likely to affect WEF security risk in many ways (Fig. 1). For instance, decreases in Colorado Front Range snowpack, resulting from changing precipitation and temperature regimes (Rasmussen et al., 2014), will likely impact water and energy security in Boulder. This is because availability of a reliable water supply in this city (like many cities) has long gone hand-in-hand with the provision of energy to power the grid, with both hydropower plants and coal-fired power plants utilizing water (Burr et al., 2011), and the grid, in turn powers the pumps that supply water to the city. In Mexico City, increases in mean temperatures and changes in rainfall are likely to affect water and food availability (Martinez et al., 2015), at the same time as extreme rain and flood events will create risks to city lives and livelihoods. Similarly, increased variability of rainfall in the Volta Basin is likely to pose risks to energy security in Accra, because hydropower generates 65% of Accra's energy (IEA, online database). Changes in precipitation will likely affect Accra's water on an even broader scale because water treatment plants and sachet water producers depend on energy to treat and package water. Climate change may in turn destabilize food security, since the agriculture sector serving urban areas largely depends on rain fed crops (Maxwell et al., 2000). In contrast to other African Cities, urban agriculture does not play a major role in Accra, as people there depend, instead, on urban food markets and street vendors who transport food from outside the city. In Accra's peri-urban areas, however, agriculture is a source of livelihood (Maxwell et al., 2000).

Three of the cities have been frontrunners in the climate risk and sustainability arena. In 2016, the city of Boulder expanded its mitigation goals and pledged to reduce greenhouse gas emissions by 80%, compared to 2005, for its government facilities by 2030, and for the entire city by 2050. The city also committed to 100 percent renewable

electricity citywide by 2030 (City of Boulder, 2016). To achieve this, Boulder will focus on three WEF security action areas: 1) it will transition to clean, renewable and local power; 2) it will foster a wise use of food, water and other resources; and 3) it will restore the health of urban, agricultural and natural ecosystems in order to sustain its communities. All actions will play a “key role in climate stability”(“Boulder City Climate Commitment Plan.pdf – January_2017.pdf,” n.d.). Mexico City launched the Program of Climate Action 2008–2012 (PAC) and the 2011 Law for Mitigation and Adaptation to Climate Change as parts of a larger 15-year “Green Agenda,” with most of designated funds committed to reducing emissions (Romero-Lankao et al., 2015). Boulder and Mexico City became members of the 100 Resilience Cities Initiative, and each has launched its resilience plan. In 2014, New York City also expanded its climate change goals to include an 80% reduction target by 2050 (Solecki, 2012). Building on its Climate Change Adaptation Task Force (2008), following Hurricane Sandy in 2013, New York launched the Building Resiliency Task Force, convened by the Urban Green Council. In Ghana, however, where energy generation is currently based on renewable sources (hydropower), climate mitigation is of lesser concern than climate risk management (MESTI, n.d.).

4. Climate risks and WEF security in selected cities

4.1. WEF infrastructure interdependencies and cascading effects

To address our first research question, here we examine how interdependencies among WEF infrastructural systems mediate (amplify or mitigate) cascading effects in two cities, Boulder and New York; and how infrastructural systems explain differences in vulnerability to the WEF security risks posed by low probability high impact extreme events (Fig. 2). Both Boulder and New York represent cities of the Global North with strong modernist urbanization ideals (Lawhon et al., 2014), in which a specific type of interdependent infrastructural systems not only shapes urban socio-ecologies but also creates specific WEF-security risks.

After sweeping through the Caribbean, Hurricane Sandy, a late-season post-tropical cyclone, hit New York City in late October 2012. The storm left 53 New Yorkers dead, hundreds of homes and 250,000 vehicles destroyed, and millions of people without power (Holloway, 2013), with economic losses of roughly $19 billion (Office of the NYC Mayor, 2013). Sandy caused large-scale destruction and the proclamation of a statewide emergency alert. Wind-related devastation and flooding disrupted the supply of water, energy, food, and other critical systems and exposed the vulnerability of interdependent infrastructures.

On October 28, New-York Governor Cuomo and President Obama declared an emergency, ordered evacuations, and during the next days launched efforts to distribute food and energy (Fig. 2, green arrow from emergency responses to food and energy). Bridges, airports, tunnels, and roadways closed, and transportation ceased. The next day, a storm surge of 4 m hit the city flooding its subway system, many suburban communities, and all road tunnels entering Manhattan except the Lincoln Tunnel. About 2.2 million residents were without power. Together with the transportation shutdown, power outages affected food suppliers, such as supermarkets, warehouses, and restaurants (Fig. 2, red arrows from transport and energy to the other sectors). In combination with flooding, this resulted in food suppliers facing a number of sanitation and food security challenges threatening the health of local populations (Wilkie et al., 2012) (Fig. 2). These events also cascaded to affect New York’s economy, health services, and the livelihoods of its residents. The New York Stock Exchange closed, so did schools, hospitals, airports, Broadway performances, and other governmental and private activities and services (e.g., flights, state courts, Fig. 2, economy and health). Numerous homes and businesses were destroyed by fire, and data and communication facilities such as the Verizon’s Telecom Hub (Troianovski, 2012) were disrupted (Fig. 2, economy and livelihoods).

New York has a well-established program to protect and enhance its water supply through watershed protection. It owns crucial land outside its boundaries, and works with landowners and communities to balance protection of drinking water with facilitating local economic development and improving waste-water treatment (Foster et al., 2011). New York’s water flows downhill from surrounding reservoirs towards the city without depending on energy-intensive pumping systems. In this way, its water and land management systems mitigate water-energy risks (Fig. 2, green arrows from water management to water and energy). However, the water system was not designed to withstand potent high impact storms such as Sandy, which have hit the U.S. with more frequency in recent years (Malo, 2013). Hurricane Sandy led to decreased drinking water quality, with turbidity measurements exceeding legal requirements, thereby impairing health and

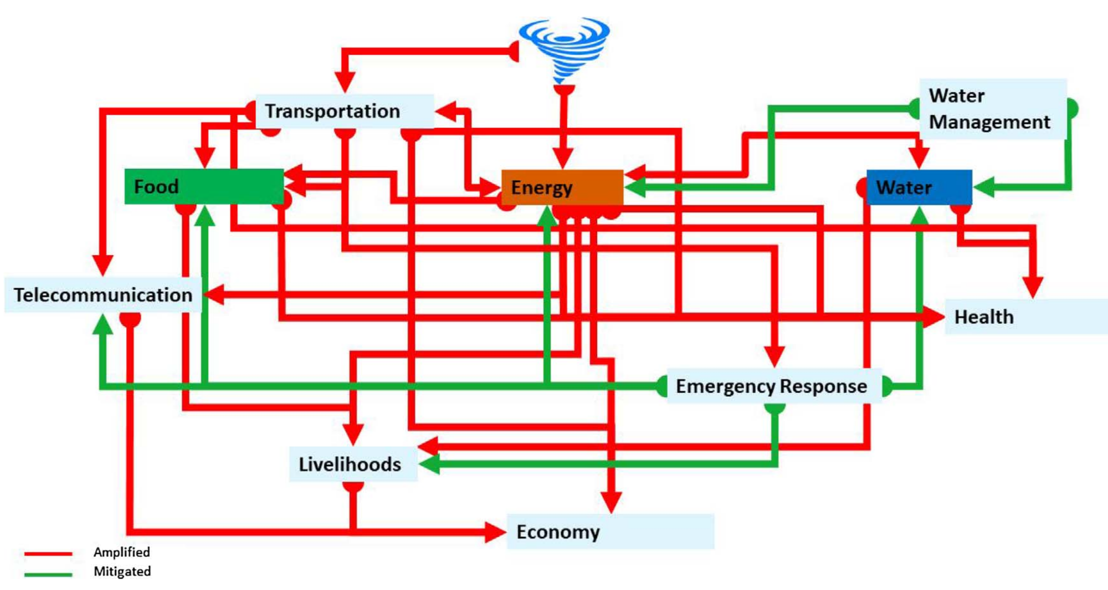

Fig. 2. Infrastructural System Interdependencies in New York. This mental model maps the factors that amplified/mitigated cascading effects triggered by Hurricane Sandy in New York. Green, positive arrows indicate risk mitigation and red, negative arrows indicate risk amplification. Own using Fuzzy Mental Modeler (mentalmodeler.com). Design by Rachel Norton. (For interpretation of the references to colour in this figure legend and text, the reader is referred to the web version of this article.)

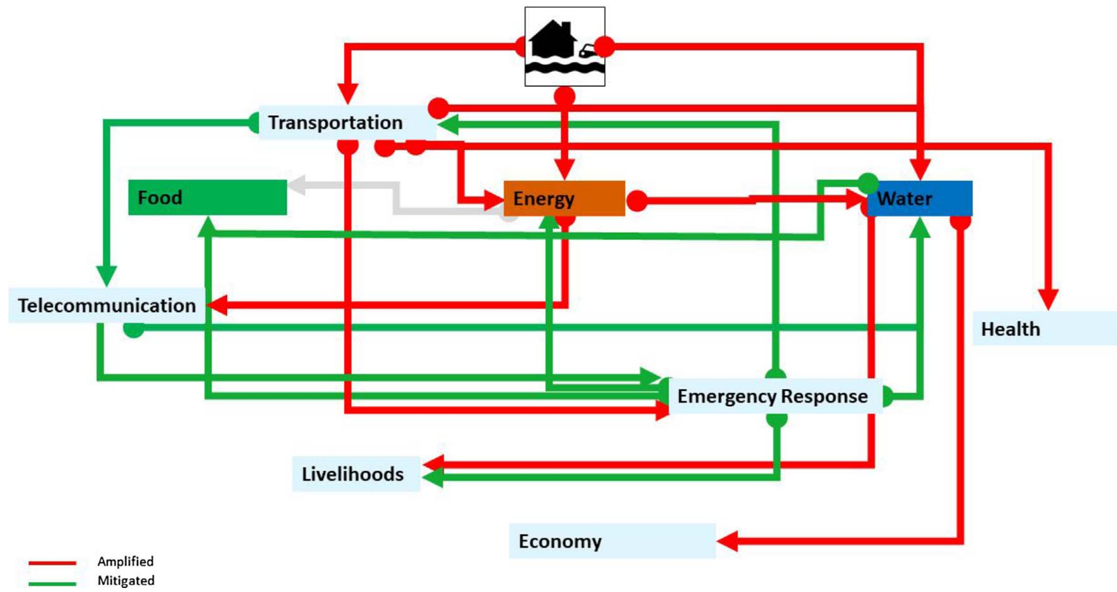

Fig. 3. Infrastructural System Interdependencies in Boulder. This mental model maps the factors that amplified/mitigated cascading effects triggered by the September 2013 Boulder Floods. Green, positive arrows indicate risk mitigation, red, negative arrows indicate risk amplification, and arrow with a question mark indicates no clear effect. Own using Fuzzy Mental Modeler (mentalmodeler.com). Design by Rachel Norton. (For interpretation of the references to colour in this figure legend and text, the reader is referred to the web version of this article.)

livelihood (Fig. 2). Adaptation measures to address this threat to water security, for example through installation of additional filtration plants, could be very costly for the city (Malo, 2013).

Between September 11th and the 15th, 2013, the Colorado Front Range, where Boulder is located, received about 431.8 mm of rain, a full 85% of its average 525 mm annual precipitation. Across the region, the flood killed 10 people, and resulted in the evacuation of 18,000. It also destroyed 688 homes and damaged an additional 9.900. While this was a historic storm, the city of Boulder was relatively well prepared to manage it.

While the Boulder flood of September 2013 was historically large enough to occur only once every 25 or 100 years, city residents and stakeholders felt they were resilient and lucky. Nevertheless, the flood's impacts cascaded to cause millions of dollars in destruction, unequally distributed across the economy and social fabric, with tangible impacts on the livelihoods and the quality of life of residents. Business, health, and education services, and cultural and academic and research centers closed (Fig. 3, economy). However, some economic sectors, such as the hardware and disaster clean up industries benefitted, as store revenues for September were doubled (MacClune et al., 2014). While homes and businesses were damaged by inundation brought about by overwhelmed drainage systems (Fig. 3, red arrows from water to economy and livelihoods), communication facilities were not disrupted, but rather served as key element of emergency responses (Fig. 3, green arrow from emergency response to water).

Similarly to Hurricane Sandy, the Boulder flood also brought into relief interdependencies and cascading effects affecting WEF security risk. By the second day of flooding, almost all the roads going west of Boulder running through mountain canyons along creeks became impassible. This threatened the city's ability to provide back-up fuel for the generator at its secondary water treatment plant, with this plant to shut down due to loss of power and excessive turbidity at the intake supply (Fig. 3, red arrow from transport to water and energy). Because the city has built redundancy through a main and a secondary potable water plant, it could withstand the secondary plant shutting down (Fig. 3, green arrow from energy to water). Only through the inventiveness of city staff, were they able to keep the main plant operational during and after the flood (Fig. 3, green arrow from emergency response to water).

The flood posed the threat of spills from the oil and gas industry as well. Spills were scattered along the Front Range, particularly in Weld County to the northeast of Boulder, which suffered from more extensive spill damage. The oil and gas companies quickly shut down nearly 1900 oil and gas wells in flooded areas, and 600 industry personnel inspected and repaired sites through advance technologies that allowed a single employee to shut down 397 wells with a laptop and an air-card (Fig. 3, green arrow from emergency response to energy) (MacClune et al., 2014). Regionally, at least 22,000 gallons of oil spilled into waterways (Fig. 3, red arrow from energy to water). Still, planning and regulations such as "setbacks from waterways, construction codes, and a requirement to report any spills to the state within 24 h" surely reduced the potential damage considerably, given the size of this decentralized industry (MacClune et al., 2014).

Most irrigation ditches in the region also experienced severe damage. However, the irrigation ditch companies promptly mitigated damage to their ditches and diversion works to get the water flowing before the next growing season (Fig. 3, green arrow from emergency response to food)(MacClune et al., 2014). Unfortunately, "most of the rebuilding was done without considering how to reconstruct diversion structures to allow for other environmental and recreational goals, such as fish passage or recreation, which weren't an issue a century ago when the structures were originally built"(MacClune et al., 2014).

4.2. Multiscale interdependencies

The cities of Accra, New York and Mexico reveal the multiscale nature of WEF risks and vulnerabilities associated with urban areas dependencies on regional and outlying regions providing them with WEF resources. They illustrate how urban WEF-Security largely hinges on events that occur in outlying basins and regions, providing cities with WEF resources, hence, playing an important, yet indirect role in the security of city dwellers. Additionally Accra and Mexico City reveal how fragmented infrastructure systems, characteristic of cities in the global South, are differently interconnected to produce different intra-urban geographies of risk inequality and exclusion.

In 2009, Mexico experienced one of its most severe droughts in decades. While the rainy season usually begins in May or June, in 2009, it was delayed by three months, affecting almost 49% of the agricultural

land inspected by the government, and causing shortfalls in the harvests of staples such as corn, beans, and wheat key to feeding the city's poor residents. As 49 percent of Mexico's farmland was impaired by harvest shortfalls, the government spent more than $100 million to buy emergency crop insurance for farmers in addition to emergency planning for food packages (Malkin, 2009).

The drought also depleted the Cutzamala system, one of the city's outlying suppliers. This forced city officials to restrict water supply in 11 urban districts for several days at a time. However, Mexico City's risks did not only result from water shortages, induced by the drought, but also from vulnerabilities of the Mexico City water system itself. Since the 1940s Mexico City has over-exploited its local water resources with current rates of extraction of between 19.1 and 22.2 cubic meters per second (Romero-Lankao, 2010). In addition to creating reductions in local water availability, this rapid extraction rate makes urban water users dependent on the availability of water from external basins, such as Cutzamala and Lerma. Thus, city residents become vulnerable to fluctuations in availability from remote water sources, fluctuations that climate change will likely aggravate (Martinez et al., 2015). Those users already facing recurrent shortages during the dry season are especially vulnerable to droughts. For example, 81.2 percent of people affected by droughts live in Netzahualcoyotl, one of the poorer municipalities of the city (Romero-Lankao, 2010).

In addition to revealing how entrenched and unevenly distributed the vulnerability of users and places is, both within the city and along the urban-rural gradient, the drought also illustrated inequalities in risk responses. During the emergency situation, trucks came to provide water to richer areas in the west, leaving poorer areas to suffer from shortages (Malkin, 2009). Such resource provision and access inequalities can lead to "local, national, and transnational potential for political instability". Indeed, urban formations themselves, along with socio-political stability, are at risk when the provision of basic services cannot be guaranteed ((WBGU, 2016), p.3).

WEF security in Mexico City faces another cross-sectoral, cross-jurisdictional vulnerability arising from linkages between water and energy and the supply of water from remote sources (e.g., from the basins of Lerma and Cutzamala). Since the 1951, interrelated energy and water insecurities have been created by the city's dependence on electrical systems to pump water up, from where it lies, hundreds of meters underground, to a city located more than 100 km away and 2200 m above sea level (Romero-Lankao, 2010). This connection is further illustrated by the fact that the Villa Victoria dam, another water supplier, was originally constructed as a hydropower plant. These linkages also reveal the failure of discharging readily available surface and rainwater, while simultaneously pumping it at an unsustainable rate.

While New York has water management and planning systems in place that mitigate the risks from extremes and enhance resilience, Hurricane Sandy illustrated the vulnerability of the city's local, regional, and global food supply networks (Wilkie et al., 2012). Like in many cities worldwide, New York's food is transported by truck, reliant on the operation of roads, tunnels, and other transport infrastructures, which suspended services during the storm. This disrupted the entire food supply chain (Fig. 2, red arrow from transportation to food). Changes in the governance of food supply chains and infrastructures explain this. During the 1980s, New York restructured its food storage and distribution systems. While the city's food previously came from farms upstate and was stored in local warehouses, today it mainly relies on food supplied from across the country, or international sources. Furthermore, US food retailers keep much smaller inventories, with reserves "sized to meet immediate demand under stable conditions, not emergency situations" (Siddhartha, 2013). The impacts of Sandy on New York's food supply illustrate vulnerabilities in urban food systems depending on globalized sources. Therefore, globalization itself has become a driver of WEF security risk (Figs. 1 and 2).

In Accra, different domains shape multiscale WEF security risks (Ndehedehe et al., 2016, Fig. 1). The first is the environmental domain. By threatening most farmers in the Northern, Brong-Ahafo and Ashanti regions of Ghana, the 2015 drought led to food insecurity in Accra, due to yam, tomatoes, cassava, plantain, maize and rice shortages. It also affected the Ghana's cocoa market that is of high importance for the economy and people livelihoods (Amponsem, 2015). Furthermore, because of Accra's dependence on the Lake Volta, for water and electricity, low water levels in the lake negatively affect the secure provision of energy and water at urban to national levels. The other two domains at play are the dynamics of the governance and technology. In Accra, the configuration of the water and energy networks is a result of urban, national and international institutional settings, policies and interventions (as it is the case for many post-colonial cities where policy reforms have been introduced from the outside). However, the built-up water infrastructure is spatially fragmented and not serving everyone in the city – still, 60 years after independence, the coverage of the networked infrastructure follows contours of the colonial city. These fragmented infrastructures lead to an array of governmental, private and often informal systems and practices supplying the city's water and energy needs, and resulting in distinct urban geographies of (in)security (Bruns, 2016). Some of these systems are fed by sources far outside the city limits, where the configuration of the WEF nexus is shaped by the activities of urban dwellers that seek to "compose new infrastructural conditions" in incremental ways (Silver, 2014: 789). Urban WEF security therefore does not stop at political-administrative boundaries, but is rather defined by the dependency of Accra from regional and remote areas (Maxwell et al., 2000; Silver, 2014).

5. Examining risk to enhance security

Worldwide, urbanization and climate change, by increasing risks from floods, droughts and other extremes, are also coalescing with multiscale domain factors to shape the likelihood of negative outcomes. Hence, and in light of actual and potential hazards and threats, it is important to generate a nuanced understanding of how governance and policy actions can mitigate climate risks while enhancing WEF security. In this paper, we applied a risk approach to security, focused on the multi-domain conditions and multiscale interdependencies that can result in uncertain and harmful outcomes. The urban realm is a place with high risk for WEF insecurity for at least two interrelated reasons. First, both the absolute demand and the need for a reliable supply of resources and services are high; and, second, the interconnectedness between sectors is usually very close, following the networked ideal of the city, tightly bound through modern infrastructural links that deliver the flow of WEF resources, often from areas outside city boundaries.

We applied our SET*E*G framework to examine pre and post-event conditions in four cities representing some of the typical WEF configurations of security risks. Each of these cities faces hydro-climatic extremes exacerbated by global warming. Another commonality is that their interdependent infrastructural systems provide critical nodes not only locally linking water, energy and food with other vital sectors (e.g., transportation and communication), but also linking the city to its providing regions. The criticality of these nodes and the interdependencies they create mean that the WEF security of cities hinges on dynamics that also take place outside their boundaries, in such regional areas as Volta (Ghana), and Cutzamala (Mexico). This pattern is repeated worldwide in remote areas and agricultural regions providing WEF services to cities, some of them quite far flung, such as those areas of the world providing New York with imported food resources. Therefore, the vulnerability (or resilience) of these remote locations is not only affected by the cities but also plays a fundamental, yet indirect, role in city WEF security.

We examined some of the mechanisms by which infrastructural systems mediate the risks from climate extremes in the cities of New York and Boulder. Our analysis shed light on the complex and dynamic nature of technological and governance failures that can amplify risks, such as the vulnerability of New York to disruptions in regional and

global food supply networks, which can be historically tracked to changes during the 1980s in the governance flood supply chains. Our analysis also illustrated how, conversely, institutional actions and infrastructural supports can prevent and mitigate the negative impacts of extreme events on the provision of electricity, food, water and other resources and services. For example, both New York and Boulder have historically developed land and water management systems that proved their capacities to mitigate water-energy risks from Sandy and the September 2013 flood respectively. The differences in governance and infrastructural conditions across the cities are key to understanding how similar hazards have the potential to result in different and uncertain outcomes, as infrastructural systems play a fundamental and complex role in mitigating – or amplifying – WEF security risks. Still, under changing societal and environmental conditions, even the most effective governance arrangements are insufficient to secure cities and their residents. Notwithstanding the cities of New York and Boulder have programs to protect their water and land resources, and regulations in place to mitigate the impacts of hazards on the security of people, both faced historically unprecedented, low probability, high impact extreme events.

The temporal and spatial diffusion of cascading effects is also mediated by a city dependence on regional and remote areas providing it with WEF resources and services. The cities of Accra and Mexico show the vulnerabilities that dependence on WEF resources from other areas can create, vulnerabilities that climate change is likely to exacerbate. All components of WEF security, risk, hazard, exposure and vulnerability, are multiscale. Thus, not only do urban infrastructural systems affect the security of urban people and places, they are also affected by multilevel actions and processes beyond city boundaries. Furthermore, our analysis shows that WEF security risk unavoidably raises equity and justice questions, such as: Who in the city has the right to use water, energy and food resources, at the cost of damaging local and remote ecosystems? Who is (or should be) responsible for ameliorating impacts, and bearing or reducing risks to populations security; and who bears (or should bear) the costs and benefits of risk mitigation and adaptation actions?

We can conclude from the above, that a critical perspective to WEF security risks is fundamental to understanding how past and present governance decisions and omissions connect inequalities in human insecurity with hazard and vulnerability complexity. For example, both currently and historically, authorities in Mexico City have engaged in water investments and policies that have favored some areas within and outside the city to the detriment of other areas, thus resulting in unevenly distributed insecurities among water users (e.g., poor populations in Iztapalapa or Netzahualcoyotl) and places (Cutzamala and Lerma). Even in New York, changes in the governance of the food system are, for sure unequally putting its people and places at risk from global food supply network vulnerabilities.

While Boulder and New York are illustrative of WEF security risks posed by low probability high impact extreme events, Accra and Mexico City exemplify governance and infrastructural arrangements that can fail even under low risk high probability extreme events. Furthermore, these cases show how history and path dependency matter. While path dependency often relates to infrastructure cost and lifecycle, it is also heavily influenced by the way that policy decisions are made within specific political contexts. Historically, governance decisions on how and where to invest in infrastructures have been left to a relatively small set of key players that bring their various interests, values, and levels of power to the table. Mexico City and Accra show how past policy actions, such as transfer of water from distant locations, at a high energy cost, or priority given to land development over risk mitigation, have shaped the vulnerability of WEF systems. In all these cases, governance arrangements are at the heart of the huge challenges decision makers and populations face in securing WEF infrastructures and services.

Particularly in Accra and Mexico City, the configuration of infrastructure networks is often based on a coming together of a mixture of urban, national and international institutional settings, policies and interventions and informal institutions and practices. Existing infrastructure networks in these cities show high levels of socio-spatial segregation and often fail to cover the complete urban agglomeration, thus creating a distinct pattern of socio-spatially differentiated risk and vulnerability. The lack of infrastructure is particularly relevant in peri-urban areas, the dynamic frontiers of urban development, where supply-systems emerge in a largely ad hoc way. As a consequence, the configuration of the WEF Nexus, as it is shaped by the activities of urban dwellers seeking to create new infrastructural conditions to meet narrowly focused needs, often develops in incremental and precarious ways. These infrastructures, and hence the WEF nexus itself, are in a constantly process of reconfiguration.

The dynamism of the processes shaping urban WEF security can be better understood by using an integrative framework to capture interdependencies among the socio-demographic, economic, technological, environmental, and governance (SET*E*G) domains. By understanding these interdependencies, cities can begin to anticipate and avoid cascading effects on WEF systems and resources. Such an understanding can help cities move towards sustainable and equitable provision and utilization of WEF resources, in support of the lives and livelihoods of their inhabitants, while avoiding negative impacts to their supporting regions and ecosystems.

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